Interstellar Travel - Challenging Propulsion and Power Technologies for the Next 50 Years

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Abstract. In February, 1999, the National Aeronautics and Space Administration's (NASA's) Jet Propulsion Laboratory (JPL) established an Interstellar and Solar Sail Technology Program, whose goal is to launch exploratory spacecraft to the near interstellar medium in the next 10 years, and to the nearest star within the next 40 years. Later that year, NASA's Sun-Earth-Connection (SEC) subcommittee established a new quest and a campaign entitled "Explore the Boundaries of the Heliospere and Near Interstellar Environment" to its roadmap theme, with the Interstellar Probe proposed to launch as a flagship mission at earliest in 2010. At last, travel to our nearby interstellar medium may be possible in the near future due to recent technological advances, especially in the areas of ultra-lightweight structures, materials, and electronics. Interstellar travel provides a challenging vision for space technologies, as velocities of up to 20 AU/Year are required for near interstellar medium travel, and up to half the speed of light are desired to reach the nearest stars. This paper will propose one vision for an interstellar program. It will include a discussion of mission concepts as well as technological requirements for accomplishing those missions.

INTRODUCTION

Ever since modern man first looked at the heavens, he has dreamed of traveling to the stars. While considering such an endeavor was laughable in the past, with today's technology it is merely impossible. Regardless, scientists and engineers alike discuss interstellar travel with great enthusiasm as it challenges their ingenuity and imagination. While the authors of this paper recognize that reaching the nearest star is improbable in their lifetime, it is not inconceivable that technologies could advance to enable interstellar travel in the next 50 to 100 years. In fact, the launch of a spacecraft to our Sun's local interstellar medium, a significant first step toward interstellar travel, might be achievable within the next 10 years.

While the interest and scientific value of traveling to another star is obvious, the merits of the trip itself are often overlooked. Investments in travel to both the near and far interstellar medium have potentially very high payoffs for the following reasons:

- Interstellar missions provide an ideal "pull" for technology advancements, including those which could greatly enhance or enable solar system missions that might not otherwise be possible.
- Interstellar missions present first-ever science opportunities which could address the most basic scientific questions including the evolution of the solar system and universe and the origins of life, and
- Interstellar travel embodies the spirit of exploration and is a magnet for capturing the public's imagination.

THE INTERSTELLAR MEDIUM AND ITS SCIENTIFIC POTENTIAL

The interstellar medium is defined as the material between stars within a galaxy. A graphical representation of our solar system and its local interstellar neighborhood is shown in Figure 1.

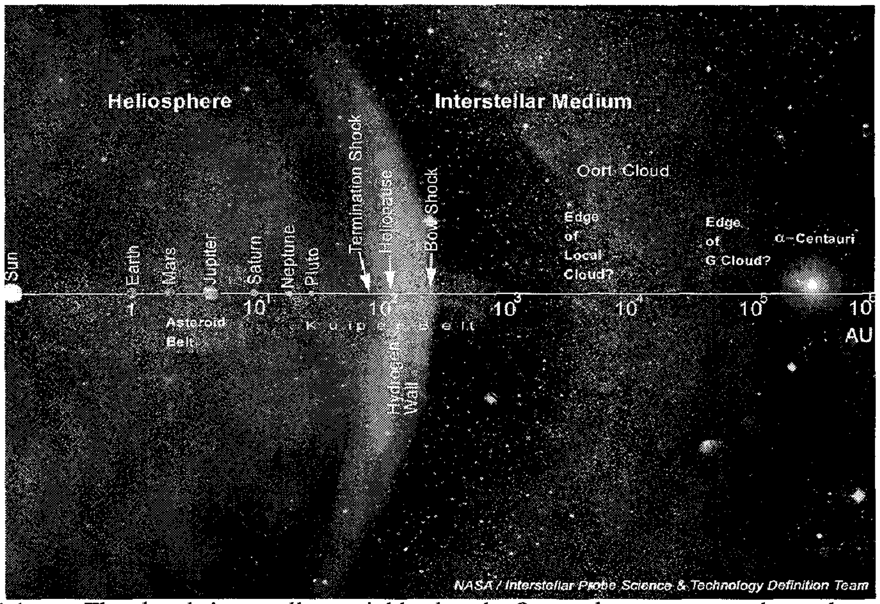

FIGURE 1. The local interstellar neighborhood: Our solar system and nearby interstellar medium on a logarithmic scale extending from <1 AU to 10^6 AU.

The interstellar medium -- containing dust, neutral gas, and charged particles (electrons and ions)--is far from uniform. The material that forms it comes from nova explosions and stellar winds. Organic material created in dense molecular clouds is thought to be sheltered inside grains of interstellar dust. Our solar system is shielded from the plasma, energetic particles and small dust and fields of the local interstellar medium by the *Heliosphere,* a low density bubble created by our Sun's solar wind. The solar wind plasma expands supersonically from the Sun, pushing aside the local interstellar medium. The diversion of the interstellar medium, flowing at 25 km/s relative to the Sun, creates an elongated heliosphere with a heliotail extending perhaps hundreds of AU downstream of the Sun. Other key features of the heliosphere (see Figure 1) include (1) the termination shock (at ~80-100 AU) where the solar wind flow drops from supersonic to subsonic velocities, (2) the heliopause (at ~150 AU) which separates the material and fields of solar origin from those of the interstellar medium, (3) the hydrogen wall, a region where interstellar hydrogen gas piles up in front of the heliosphere, and (4) the bow shock, a shock which is merely speculated, created as our solar system travels at hypersonic velocities through the interstellar medium (Liewer, Mewaldt, 2000).

Straddling the boundaries of the heliosphere is the Kuiper Belt, a grouping of planetoids, small objects and dust beyond Neptune, which is thought to be the source of short period comets. Presently we have no measurements of any Kuiper Belt Objects beyond 50 AU. Small orbiting objects and dust are expected to exist far beyond Neptune, and their density and distribution are important in understanding the mass and characteristics of our Sun's primordial disk and the evolution of our solar system.

Our Sun and heliosphere are thought to be passing through a Local Interstellar Cloud (LIC), which consists of low density (≈0.3/cc) material (mostly neutral hydrogen) blowing at us from the direction of the star-forming regions within the constellations of Scorpius and Centaurus. Current estimates are that the edge of the local cloud could be 50,000 AU or 10,000 years away in the direction of our travel. Astronomical observations suggest that a group of clouds, referred to as the G complex, lies beyond our local cloud. The material here is thought to be much denser and, as the Sun moves into this material, the heliosphere will shrink, moving the heliopause inward to well within the solar system.

The edge of our Sun's sphere of gravitational influence is marked by the Oort Cloud, thought to be a more or less spherical shell of comets. The Oort Cloud is presently thought to extend from ~10,000 AU to ~100,000 AU. Objects and dust extending out to and in the Oort Cloud are of scientific interest again, because they are key in understanding the mass and distribution of our Sun's primordial disk.

Beyond the Oort Cloud, the next known major feature is the nearest star system, Alpha-Centauri. Alpha-Centauri is located at approximately 4.3 light years away (~270,000 AU). The nearest star that shows evidence of a planetary system is Epsion Eridani, which is approximately 10.5 light years away.

The scientific importance of sending a spacecraft through the heliosphere and local interstellar medium and to the nearest star, is directly in line with NASA's Space Science Enterprise Mission which is to

- Solve Mysteries of the Universe
- Explore the Solar System
- Discover Planets Around Other Stars, and
- Search for Life beyond Earth.

The scientific importance of interstellar travel crosscuts between all four of the NASA strategic themes (NASA Office of Space Science, 1977), and is directly in line with many of key questions identified by these themes:

1. *Sun Earth Connection (SEC) Theme* - Interstellar exploration can help to address one of the fundamental quests of this theme which is "How do the Sun and galaxy interact". In fact, travel through the heliosphere and into the interstellar medium is the only way to determine the size of the heliosphere, to provide *in-situ* measurements of the interaction between our Sun and the galaxy, and to determine the composition of the local interstellar medium. For this reason, the SEC theme has acknowledged the importance of interstellar exploration by including both the Interstellar Probe Mission and Interstellar Trailblazer Mission in the SEC Strategic Plan.

2 *Origins (ORG) Theme* - Interstellar exploration has applicability to all four of the Origins theme goals, namely: 1) To understand how galaxies form in the early universe, 2) To understand how stars and planetary systems form, 3) To determine whether habitable or life-bearing planets exist around nearby stars, and 4) To understand how life forms and evolves. One example of how interstellar exploration can help to address these issues is by characterizing the nearby interstellar "soup". The quantity and content of organic material in this "soup" could change theories regarding the prevalence or scarcity of life in the universe. In addition, from a vantage point beyond the solar system and its infra-red obscuring dust cloud, measuring the cosmic infrared background radiation can provide fundamental information on how the first stars and galaxies formed.

3. *Solar System Exploration (SSE) Theme* - Interstellar travel can address issues directly applicable to three of the five the SSE goals which include: 1) Understand the nature and history of our Solar System, 2) Understand the external forces, including comet and asteroid impacts, that affect life and the habitability of Earth, and 3) Understand how life may originate and persist beyond Earth. Our solar system and its influences extend well beyond the ninth planet Neptune. It also includes the objects of the Kuiper Belt and beyond. The solar system primordial disc, in fact, extends all the way to the Oort Cloud, estimated to be tens of thousands of AU from our Sun. It is impossible to understand our solar system without extending exploration to its outer boundaries and determining the density and distribution of matter throughout

4. *The Structure and Evolution of the Universe (SEU)* - Interstellar exploration has direct application to the following SEU quests: 1) What are the cycles of matter and energy in the evolving Universe?, and 2) How did the structure in the Universe form? These questions can be addressed by both remote sensing and *in-situ* measurements. Direct sampling of the dust, neutral and ionized matter of the interstellar medium will provided fundamental information on the chemical evolution of matter in the galaxy and also on the ionization state of the

interstellar medium. As mentioned above, measuring the cosmic infrared background radiation can provide fundamental information on how the first stars and galaxies formed.

VISION

The vision for interstellar travel is to send an exploratory spacecraft to the nearest star in less than 50 years, with the short term goal of launching a spacecraft to the nearby interstellar medium in the next 15 years. This program would be executed in phases with progressive technologies enabling travel to the next interstellar boundary. See Figure 2.

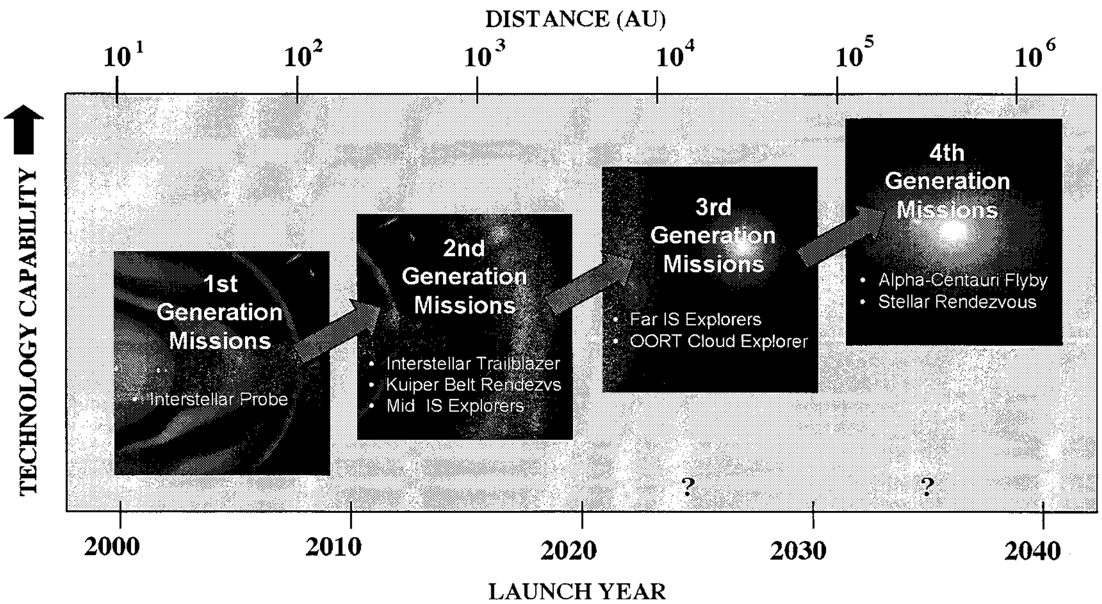

FIGURE 2. A Vision for Interstellar Exploration

First Generation Mission - The Interstellar Probe

First generation interstellar missions would include travel through the heliosphere and into the nearby interstellar medium. The Interstellar Probe Mission is designed to do just that, and is currently identified in the NASA Strategic Plan for the Sun-Earth-Connection Theme. The mission goal is to deliver a scientific payload of 25 kg to 200 AU in < 15 years, with an extended mission to 400 AU. During summer and fall of 1999, a team of 30 scientists worked with JPL engineers and technologists to define this mission concept (JPL Interstellar & Solar Sail Technology Program, 1999). The principle scientific objectives of this mission are the following:

- Explore the nature of the interstellar medium and its implications for the origin and evolution of matter in our galaxy and the universe;
- Explore the influence of the interstellar medium on the solar system, its dynamics, and its evolution;
- Explore the impact of the solar system on the interstellar medium as an example of the interaction of a stellar system with its environment;
- Explore the outer solar system in search of clues to its origin, and to the nature of other planetary systems.

One example mission design includes launching a Delta II 7425 launch vehicle in 2010 (Note: The actual launch time is likely to be much later), with a flight system launch mass of 599 kg. Shortly after launch, a solar sail is deployed and its stowage/deployment devices jettisoned. See Figure 3. Solar photon pressure on the sail is then used to alter the flight path, sailing the spacecraft to within 0.25 AU of the Sun. The sail is then maneuvered to maximize photon "push" away from the Sun, and the spacecraft is accelerated to velocities up to 67 km/s. At approximately 5 AU, the sail propulsion contribution is minimal, and the sail is jettisoned to prevent potential interference with sensitive instrument detectors. The mission design includes accelerating the probe toward the nose of the heliosphere, which provides the shortest path to the local interstellar medium. See Figure 4. On its way, the spacecraft will take numerous observations of our Sun, the Kuiper Belt, the Heliosphere and the local interstellar medium using a suite of fields, particles and optical instruments.

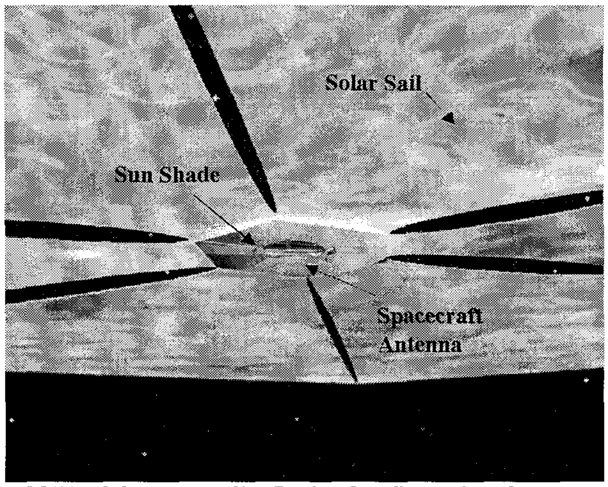

FIGURE 3. Interstellar Probe Configuration Concept

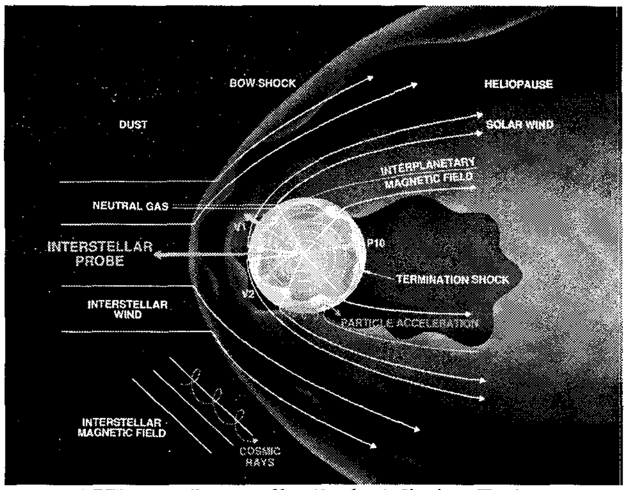

FIGURE 4. Interstellar Probe Mission Trajectory

The prime spacecraft structure is a 2.8 m antenna with instruments and equipment located on its edges and backside. The 191 kg spacecraft is suspended in a 11-m hole, centered within the sail. The 400 m diameter, 1 g/m2, 123 kg, carbon microtruss, spinning, hexagonal sail is capable of withstanding extreme temperatures as it passes by the Sun at 0.25 AU, and is maneuvered by moving the spacecraft center-of-mass relative to the system center-of-pressure. Note: Nuclear Electric Propulsion is another technology which could meet the needs of this mission. It was not baselined as part of the study, however, due to interference with science instruments, and capabilities which are mismatched for relatively small payloads.

The mission assumes Ka-band for uplink and downlink communications, with a 350 bps downlink rate at 200 AU. This is achieved using a 33W Ka-band RF whose power could be supplied by 3 Advanced Radioisotope Power System (ARPS) units (based on AMTEC technology). Next generation system-on-a-chip electronics, micro-spacecraft technology and advanced packaging techniques are also assumed. Instruments were constrained to weigh no more than 25 kg total, and are expected to meet the science objectives described above using the following measurement strategy:

- Measure, in-situ, the properties and composition of interstellar plasma and neutrals, lower energy cosmic rays and interstellar dust.
- Determine the structure and dynamics of the heliosphere with in-situ measurements and global imaging, and
- Map the infrared emission of the zodiacal dust cloud, measure in-situ the distribution of interplanetary dust, and determine the radial distribution of small Kuiper Belt objects.

Second Generation Mission - Mid Interstellar Explorers

Second generation missions would include either 1) Travel to further reaches of the near interstellar medium (100's of AU to 1000's of AU), or 2) Rendezvous with Kuiper Belt objects. These missions would require advanced propulsion technologies which might be available in the 2010 to 2020 time frame. Two mission concepts which have been explored in studies include the Interstellar Trailblazer and the Kuiper Belt Observer (KBO) missions. The Interstellar Trailblazer mission is currently listed as a potential far-term mission in the NASA Strategic Plan for the Sun-Earth-Connection Theme. The KBO mission is currently not in the NASA Strategic Plan, however, it was considered for addition to the plan by both the Origins and Solar System Exploration Themes.

Interstellar Trailblazer

The goal of the Interstellar Trailblazer mission is to study our Local Interstellar Cloud (LIC), a low-density "bubble" that our Sun is currently traveling through, whose edge may be as near as 1000's of AU. Instruments on-board the Interstellar Trailblazer would study the composition, density, temperature, ionization state and dust content of this cloud, and how they vary with time and location (Wallace, Ayon, 2000).The scientific objectives of this mission as described in the SEC Roadmap are the following:

- Determine the nucleosynthetic state of matter in our local cloud.
- Catalog the identities and abundances of organic and inorganic molecules in the interstellar medium and outer solar system,
- Determine the detailed composition of interstellar dust.
- Measure the complete charge-state distribution of elements in the interstellar medium.
- Search for predicted sources of low-energy cosmic-ray antiprotons and positrons from black holes and dark matter annihilation, and
- Explore the nature of the galactic environment that our solar system will occupy over the coming centuries.

The mission profile is similar to that for the Interstellar Probe, however, it is much more technically aggressive. The mission goal is to deliver an instrument package to 2000 AU within 30 years of launch. After launch, a 1 km diameter, 0.1 g/m^2 solar sail is deployed and is guided to within 0.1 AU of the Sun before it is accelerated to velocities of 67 AU/year. The solar sail is jettisoned at approximately 5 AU to avoid interference with sensitive instruments. See Figure 5. In addition to advanced sail systems, the mission assumes advanced power and telecommunication systems and a highly autonomous spacecraft. Instrument measurement objectives include the following:

- Determining the distribution of matter in our Local Interstellar Cloud (LIC) using advanced, high resolution spectrometers, and
- Measuring the elemental, isotopic, and molecular composition of interstellar plasma, neutrals, low energy cosmic rays, and dust.

Kuiper Belt Observer (KBO)

In May of 1999, a study was performed to develop a Kuiper Belt rendezvous mission, for possible inclusion in the NASA Strategic Plan (JPL Advanced Projects Design Team, 1999). The resulting Kuiper Belt Observer (KBO) mission was designed to provide in-situ exploration of both a large (200-500 km) and a small (1 - 5 km) Kuiper Belt object, and to flyby and provide remote sensing of a Centaur object. The scientific objectives of this mission are given below:

- Study reservoirs of primitive materials.
- Study the early phases of the solar system origin and evolution
- Determine the processes that guide the origin and evolution of small bodies, and
- Probe the prebiotic chemistry of the early solar system.

The proposed mission would launch during the 2015 timeframe or later on a Delta IV heavy launch vehicle. The spacecraft is comprised of the following: 1) The carrier spacecraft with onboard science, 2) Two Kuiper Belt Object landers, and 3) A Nuclear Electric Propulsion (NEP) system. A Solar Concentrator/Solar Electric Propulsion system might also be used to accomplish this mission (either solar thermal/dynamic or photovoltaic). This propulsion option was not baselined because of high cost estimates, potential technical difficulties in developing a 1 km mirror concentrator, and concerns for the environmental survival of large photovoltaic arrays (for that option only).

During its 12-year cruise, the 1000 kg spacecraft would measure the distribution and composition of interplanetary dust. Approximately five years after launch, the spacecraft would flyby and perform remote sensing on a Centaur object (Nessus, Pholus, or Chiron), and would begin its 7-year coast period. Approximately 12 years after launch, the propulsion system would thrust in the opposite direction to slow the spacecraft down before reaching the first large Kuiper Belt Object at 40 AU. There, it would jettison one lander for rendezvous and 40 days of in-situ science operations. In-situ lander operations would include the collection of at least one 10 m core sample from the object. After completion of the first Kuiper Belt Object rendezvous, the spacecraft would then rendezvous with a smaller object where it would deliver a second lander for in-situ observations. The end of mission would occur at Launch + 15 years.

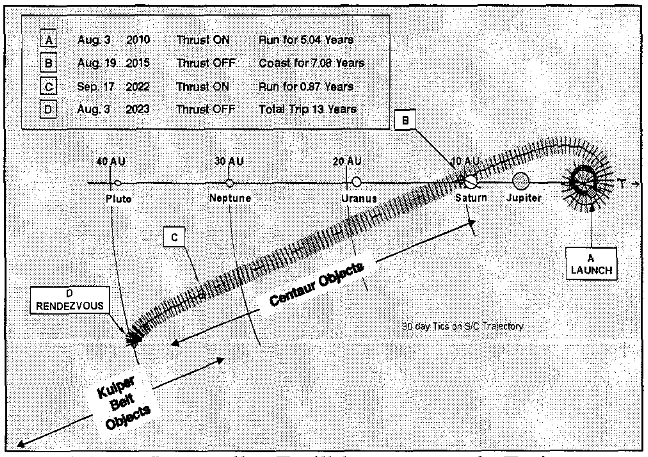

FIGURE 5: Interstellar Trailblazer Example Trajectory

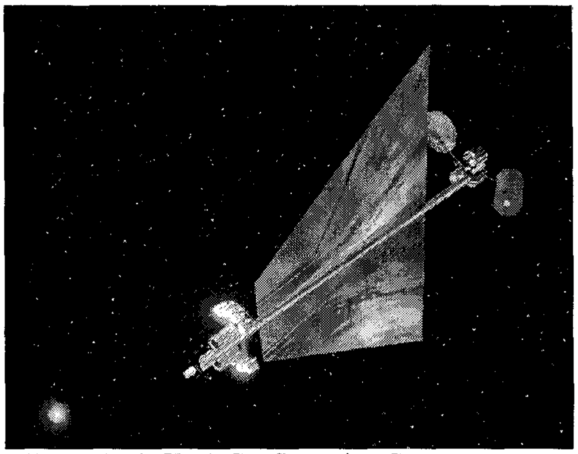
FIGURE 6. KBO Configuration Concept

Technologies required for this mission include light weight electronics, a 85-105 KW nuclear power system with 7 year full power output, large lightweight trusses and radiators, a Ka-band telecom system capable of 30 kbps at 43 AU, an autonomous soft landing system, ARPSs, cold helium thruster systems (for the landers to prevent surface contamination), and advanced drilling systems.

Third and Fourth Generation Missions

Third generation interstellar missions would include travel to the far reaches of the near interstellar medium (1000's of AU to 100,000's of AU) and the Oort Cloud. These missions would require yet another leap forward in propulsion technologies which might be available in the 2020 to 2030 time frame. Fourth generation missions would include travel to the nearest stars (4.3 to 40 light years, or 270,000 AU to 2,500,000 AU). First missions would likely flyby one of the nearest stars like Alpha Centauri at 4.3 light years distance. The next step in technological breakthroughs would then allow for a rendezvous of one of the nearby stars, and possibly even landing.

Because these missions are probably 30-100 years in the future, any evaluation of candidate technologies to achieve them would certainly be speculative. Although only 1 in 1,000,000 technologies might pay off for reaching these ultimate destinations, the possibility will always exist as long as humans continue to push forward and explore. In the meantime, the technological advances achieved in the effort will probably provide their own rewards.

TECHNOLOGIES

Technology Requirements for the Next 10 Years

In order to launch first generation interstellar missions such as the Interstellar Probe, investments in key technologies such as those defined below are required (JPL Interstellar & Solar Sail Technology Program, 1999):

Instruments - The interstellar medium is populated by low particle fluxes (10-3 particles/cm2, 10000 times less than current measurement capabilities) and small magnetic fields (<0.01 nT, 10 times smaller than current measurement capabilities). This requires breakthroughs in sensor technologies and lightweight booms. The need for a low spacecraft total mass requires that the full compliment of fields, particles and magnetic instruments weigh ≤ 25 kg, or less than half the mass of the Ulysses instrument suite.

Electronics - The miniaturization of electronics consistent with other deep space programs (e.g. X2000) is required to perform the Interstellar Probe Mission. Continued investment and progress in advanced, system-level, integrated, electrical/mechanical packaging (e.g. electronics in structure, wireless communications, and distributed systems) is also necessary in order to meet spacecraft mass requirements.

Autonomy - Travel to distances out to 200-500 AU will result in one-way telecommunications delays of up to 3 days. Thus, the quickest ground response time to a spacecraft fault or operation requiring ground feedback would be on the order of a week. Obviously, next generation autonomous spacecraft operations, navigation and control are required to execute such a mission.

Solar Sails - Solar sails are becoming feasible due to recent advancements in materials and lightweight structures. Sail requirements for first generation interstellar missions are variable and dependent on the spacecraft mass and flight time, the sail radius and areal density, and the distance of closest approach to the Sun (See Figure 7). A representative sail design capable of supporting the proposed Interstellar Probe Mission might include a spinning sail structure 400 m in diameter, with an aerial density of 1 gm/m^2 (including support structure), and a sail material capable of withstanding a peak temperature of 575 K (860 K at wrinkle points). To support trajectory maneuvers, the navigation and control design would have to support a < 8degree per day sail procession rate.

Nuclear Electric Propulsion (NEP) - NEP is a viable alternate to solar sails as a propulsion technology for near term interstellar mission needs. NEP design parameters can be traded against flight time, delivered mass, and NEP specific mass (See Figure 8). Specific technology needs in this area include the following: 1) A space reactor with an operating life ≥ 10 years, 2) A lightweight Rankine power conversion system, and 3) A lightweight, deployable, large-area radiator.

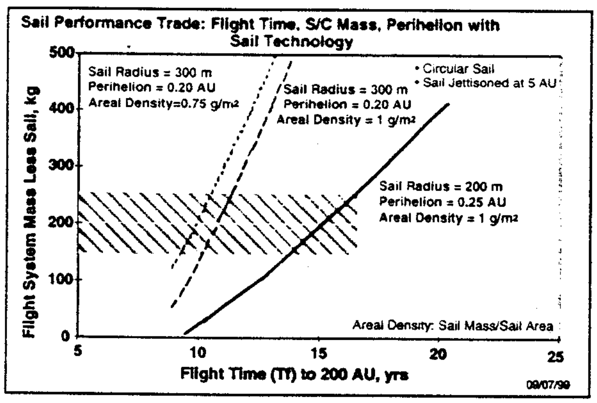

FIGURE 7. Solar Sail Performance Trades for Interstellar Probe Mission

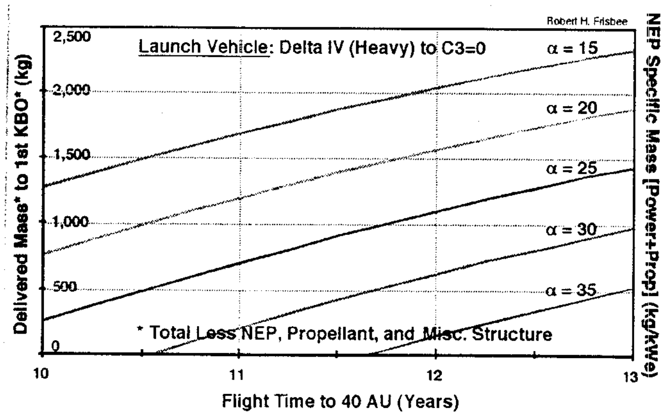

FIGURE 8. NEP Performance Trades for Kuiper Belt Observer Mission

Power - Nuclear fission reactor systems appear to be the most promising candidates for meeting near interstellar power needs in the next 15 years. For the representative Interstellar Probe Mission, three second-generation Advanced Radioisotope Power System (ARPS) were baselined which used Alkali Metal Thermal-to-Electric Converters (AMTECs). This power system was assumed to deliver 273 W to the spacecraft bus at Launch + 15 years, and 228 W to the spacecraft bus at Launch + 30 years. Each ARPS unit was targeted to weigh ≤ 8.5 kg.

Telecommunications - Both Ka-band and optical communications can probably meet the telecommunications needs for most near term interstellar missions. To support the representative Interstellar Probe Mission, a Ka-band system was baselined because it was thought that the technology was more likely to be ready to support missions launching in the next 10 years. It was also more capable of supporting telecommunications requirements in the inner solar system. (Note: For solar sail missions requiring near Sun trajectories, extreme ranges in Earth-Spacecraft-Sun angles and distances require a diverse and complex communication system). The Ka-band design baselined for this mission includes a $\geq$ 350 bps downlink rate and $\geq$ 15 bps uplink rate at 200 AU. This assumed a 3 rpm spacecraft spin rate and a 2.78 m diameter spacecraft antenna (capable of fitting within a Delta II launch vehicle). Technologies required to support this design include the following: 1) Second generation Space Transponding Modems (STMs), 2) Lightweight Ka-band antennas, 3) High efficiency (45% efficient) Solid State Power Amplifiers (SSPAs), 4) High Power (~5 kW RF) Ka-band Ground/DSN Transmitters, and 5) DSN 34 m HEF and 70 m antenna upgrades to support Ka-band communications, including improvements to achieve $\geq$ 0.5 db gain and gain uniformity between 10 degrees elevation and zenith.

Some of the key technical needs for developing an optical communications system for the ISP mission are the following: 1) A spacecraft transmitter optical chain capable of pointing the 6 microradian optical beam to better than 0.5 microradians in the context of a spinning spacecraft to maintain a link, and 2) A ground system with either large power laser(s) or an adaptive optic system, and 3) An understanding of the effects of propagating high power lasers through the Earth's atmosphere.

Studies performed at JPL indicate that technologies required for launching a near interstellar probe mission by 2010 could be demonstrated through a series of space demo flights and missions. A roadmap showing how this might be accomplished is shown in Figure 9.

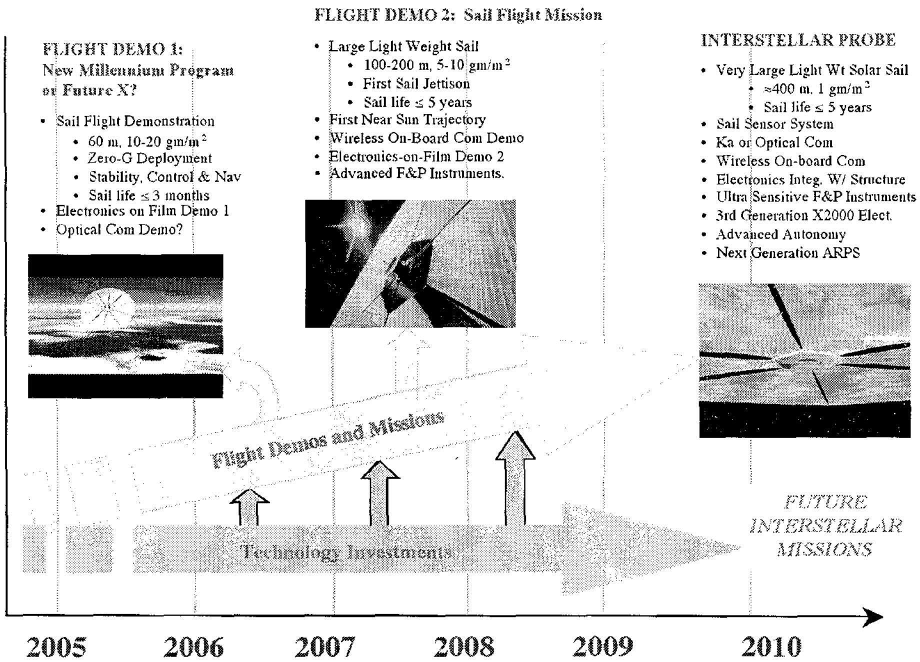

FIGURE 9: Example Roadmap for Technology Demonstration Missions Leading to Near Interstellar Medium Travel in the Next 10 to 15 Years.

Technology Requirements for the Next 50 Years

The technical challenges involved with sending a spacecraft to the nearest star are numerous and daunting. The most obvious challenges, however, are those related to propulsion and telecommunications.

To put the propulsion challenge in context, consider the velocities required to reach our nearest star Alpha Centauri within the span of a human life. See Table 1 (Frisbee, 1999). To put the communications challenge in context, consider the one-way light times for missions to our local interstellar neighborhood. See Table 2.

TABLE 1. Travel to Alpha Centauri (4.3 light years) - Within the Span of a Human Life

Travel Time	Velocity	Energy Required	Comment
≤ 10 years	0.50 c	≈ 10^{19} Joules	Approximately the current output of human civilization for 10 days
≤ 40 years	0.11 c	≈10^{18} Joules	Approximately the current output of human civilization for 12 hours or 130 M-Tons of TNT
≤ 100 years	0.04 c	≈10^{17} Joules	~1.5 times the energy of the 1908 Tunguska comet impact
≤ 74,000 years	0.006 c	≈10^{11} Joules	Travel time for Voyager I, assuming it were travelling in the direction of Alpha Centauri.

TABLE 2. Communications Delays for Spacecraft Traveling in Interstellar Space

Launch Date	Mission	Spacecraft Distance	One-Way-Light Time
2010	Interstellar Probe	200 - 500 AU	1 to 3 days
2020	Interstellar Trailblazor	2000 AU	12 days
2035	Oort Cloud Explorer	10,000 AU	60 days
2050	Alpha Centauri Flyby	270,000 AU	4.3 years

While the authors of this paper would not presume to know what technologies might become available to succeed in accomplishing such missions, some cursory studies have been performed (Frisbee, 1999. A highly speculative roadmap, showing which of the known propulsion and telecommunications technologies might enable interstellar travel, is given in Figure 10.

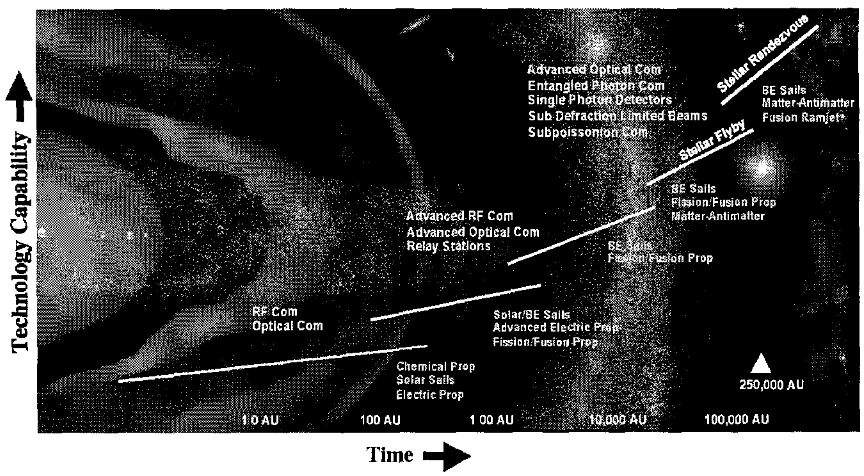

FIGURE 10: Representative Roadmap for Telecommunication and Propulsion Technologies Which Might Lead to Interstellar Travel

SUMMARY

While sending a spacecraft to the nearest star is probably not realizable in the authors' lifetime, advancements in technology might make it possible in the next 50 to 100 years. Even small steps toward this goal, such as launching missions to our nearby interstellar medium, have potential high technological and scientific payoffs.

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